Solar Neutrinos / Stellar Processes Working Group Executive Summary*

Working Group Leaders: Thomas Bowles (tjb@lanl.gov); Concha Gonzalez-Garcia (Concepcion.Gonzalez-Garcia@cern.ch), Michael Wiescher (mwiesche@darwin.helios.nd.edu)

Introduction

The field of solar neutrino research has provided significant new information on the properties of neutrinos: in particular, the Sudbury Neutrino Observatory (SNO) has recently produced a model-independent demonstration that solar neutrinos undergo flavor transformation. It is clear that solar neutrinos allow insight into the ν sector as well as providing a probe of stellar processes. Indeed, these two activities are strongly coupled and both are required in any study of ν or stellar properties. It is clear this field offers well-defined opportunities to further extend our knowledge of the properties of neutrinos and for processes that are of primary importance in solar fusion and supernova explosions.

Importance of Future Solar Neutrino Experiments

For the foreseeable future, solar neutrinos will provide the only intense source of ν_e. The primary goal of future solar neutrino experiments will be to directly detect the low-energy part of the ν spectrum in real time, allowing for an independent measurement of the dominant flux of solar neutrinos - the p-p neutrinos. Such experiments will also provide a measurement of the ν fluxes from the ^{7}Be reaction and the CNO cycle. These measurements will allow for: (i) a direct test of the Standard Solar Model (SSM) and (ii) an improvement in our understanding of the properties of neutrinos.

A Direct Test of the SSM

Solar ν experiments (coupled with an understanding of ν properties) provide a stringent test of the SSM. For instance, as the fusion reactions that produce the different sources of neutrinos have different radial distributions, a full set of solar neutrino measurements allows one to probe the radial temperature dependence of the Sun. At present, the Ga, Cl, SuperKamiokande, and SNO experiments provide the following 1-σ uncertainties in the fluxes: $\delta f(\text{p-p}) = 18\%$, $\delta f(^7\text{Be}) \approx 35\%$, and $\delta f(^8\text{B}) = 13\%$, with the uncertainties in the p-p and ^{7}Be fluxes strongly correlated. In the near future, one can expect that with improved Ga, SNO, KamLAND, and Borexino results, one can achieve the following 1-σ uncertainties: $\delta f(\text{p-p}) = 12\%$, $\delta f(^7\text{Be}) = 8\%$, and $\delta f(^8\text{B}) = 8\%$.

The need for improving the accuracy of the measured fluxes can be questioned as the p-p flux is claimed to be known to 1% accuracy from the SSM. In fact, this quoted uncertainty is not SSM independent and the p-p flux is not completely determined by the solar luminosity. On the contrary, the predicted value of the p-p flux strongly depends on details of the solar model that, in particular, determine the ratio of the rates of the two primary ways of terminating the p-p fusion chain. The direct measurement of the p-p and ^{7}Be fluxes will allow us to test the SSM prediction for this ratio. This is a critical probe of solar fusion. Thus, in order *to provide a much more sensitive test of the SSM (at the % level), precision measurements of the total flux of the low-energy p-p and ^{7}Be neutrinos are required.*

Improving Our Understanding of the Properties of Neutrinos

Solar ν experiments that detect the charged-current (CC) interactions of ν_e measure the product of the solar flux times the survival probability for ν_e. Experiments detecting the electron scattering (ES) of ν_e measure, in addition, a contribution from the neutral current (NC) interaction of all ν active flavors, which is dependent on the conversion probability from ν_e to ν_μ □□□ ν_τ. The implication of these observations depends on the particle physics scenario considered for flavor mixing.

a) Current status of our knowledge

All of the data presently available provide us with the following picture: 1) the high-energy ^{8}B neutrinos have a large non-ν_e component, 2) the survival probability for $E_\nu > 5$ MeV is essentially independent of energy, and 3) the survival probability increases at low energies (p-p and ^{7}Be neutrinos).

b) Assuming 3 neutrinos generations and CPT is conserved

Under this hypothesis, solar ν experiments that measure CC and/or ES can independently determine the flux of solar neutrinos and the survival probability of ν_e. This in turn determines the conversion probability into other active flavors by unitarity. Thus, experiments detecting the low-energy part of the solar neutrino spectrum will be able to determine the relevant ν_e survival probability at low energies.

The observations to date can be explained under one of the following three hypotheses: mass-induced flavor oscillations, flavor-changing neutral currents (FCNC), or resonant spin-flavor flip conversion (RSFF). If FCNC or RSFF account for the observed flavor transformation, future solar neutrino experiments are the best (and possibly only) means of probing this new physics. The effective survival probabilty for p-p neutrinos for these two scenarios differ by more than 10% and therefore the measurement of the p-p rate will discriminate between these two possibilities.

If active oscillations are the source of the flavor conversion, then the Large Mixing Angle (LMA) solution is highly favored, but the LOW and VACuum solutions cannot be completely precluded. We should soon know from the KamLAND and Borexino experiments if flavor oscillations are the explanation for the solar neutrino results. Of course, the possibility exists that KamLAND and Borexino may not observe effects consistent with flavor oscillations. In that case, it will certainly be essential to extend solar neutrino studies to lower energies in order to investigate the origin of the observed flavor oscillations as discussed above.

Assuming three active neutrino flavors (to accommodate the solar and atmospheric data), the mass states can always be labeled in the form that solar neutrinos are dominated by the mixing of the neutrino eigenstates ν_1 and ν_2. Thus, solar neutrino experiments are a primary source of information on δm_{12}^2 and θ_{12}. At this point, the best-fit LMA solution has $\delta m_{12}^2 \approx 6 \times 10^{-5}$ eV^2 and $\theta_{12} \approx 32°$. The uncertainties at the 90% C.L. allow $3 \times 10^{-5} \leq \delta m_{12}^2 < 2 \times 10^{-4}$ eV^2 and $26° < \theta_{12} < 36°$. KamLAND is expected to be able to define the allowed δm^2 range to 10-30% accuracy (worsening rapidly for higher values of δm^2). However, it will only improve our knowledge of the mixing angle slightly as their ultimate accuracy on the mixing angle is limited by their knowledge of the overall flux normalization. Similarly, if the LMA solution is the correct one, Borexino will provide information that is important for the neutrino sector and astrophysics, but it will not improve our knowledge of the mixing angle.

Future solar neutrino experiments that are sensitive to the low-energy p-p neutrinos provide the best prospect for improving our knowledge of θ_{12}. In order to achieve a sensitivity comparable to that projected for KamLAND, one needs to measure the p-p flux with the same accuracy as KamLAND expects for their overall flux normalization (which may range between 3% and 10%). In order to be comparable to the existing uncertainty in θ_{12} set by all available solar ν data, one needs to achieve an accuracy of 3%. This is no doubt a challenging proposition, yet a general goal of the next-generation solar neutrino experiments is to achieve 1% statistical accuracy. Since the ES cross section is known with great accuracy, one may be able to achieve comparable systematic uncertainties in ES experiments. The accuracy of CC experiments will likely be limited to a few percent by the uncertainty in the CC cross-section (which will be calibrated using intense artificial ν sources). An alternative approach (separating CC from NC in an ES measurement) may be able to overcome that limitation.

c) Allowing for the existence of sterile neutrinos in flavor oscillations

If a sterile neutrino exists, solar ν_e can oscillate into an admixture of active and sterile states. In this case, the determination of the oscillation probabilities requires one to compare the sum of CC and NC measurements with an accurately known flux of neutrinos. At present, this is done by comparing the measured CC + NC flux of ^{8}B neutrinos with the SSM prediction. Allowing the total ^{8}B solar ν flux to be greater than the SSM prediction results in a limit on a possible sterile component of ^{8}B neutrinos of ≈50% (90% CL). In the near future, if LMA is correct, KamLAND (together with the SNO CC and NC data) will provide a sensitivity of ≈ 13% for a sterile component of the ^{8}B neutrinos.

Improving substantially on the above limits for a sterile-ν admixture requires precision flux measurements of the low-energy (p-p and ^{7}Be) solar neutrinos. In order to do this in a SSM-independent way, one must extrapolate the suppression factor measured by KamLAND to lower energies and then measure the CC and NC p-p and ^{7}Be rates. In this case, the sensitivity is determined by the uncertainty in extrapolating the suppression factor (which is again limited by the overall normalization uncertainty in KamLAND) and the accuracies of the CC and NC p-p measurements. A model-dependent test can be made using the SSM prediction for the p-p flux and measuring the p-p CC and NC fluxes. Thus, one sees the need to push for accuracies in the CC and NC p-p fluxes in the percent range.

In any case, studies of possible sterile-ν admixtures in more general scenarios imply that the sterile component of the solar neutrino fluxes may be energy dependent. Thus, *low-energy solar neutrino experiments must necessarily be a part of any full study of sterile neutrinos.*

d) Allowing CPT violation with flavor oscillations

Since neutrinos have no intrinsic charge, they provide a unique probe for testing for a violation of CPT. If CPT is violated, the neutrino mass scales and mass differences will in general be different for ν and $\bar{\nu}$. Thus, a test for CPT violation in flavor oscillations must necessarily include both ν and $\bar{\nu}$ measurements. If KamLAND finds an oscillation signal, it will determine the oscillation probability for $\bar{\nu}$. Then, assuming that Borexino agrees with the expected LMA solution (if it does not, CPT violation will have been already been discovered), a *test of CPT* will need a determination of the ν_e survival probability with equivalent precision. This *requires a measurement of the p-p rate to accurately measure the neutrino oscillation parameters*. This will allow in some models a constraint on the source of CPT violation at a scale < 10^{-20} GeV, which can be compared with the present CPT test from the upper limit on the mass difference in the kaon system of <4.4 x 10^{-19} GeV.

e) Limits on a neutrino magnetic moment

If neutrinos have a magnetic moment, their interaction cross section for ES will be substantially modified due to the electromagnetic interaction. This will result in a distortion in the spectrum of the scattered electrons. This effect is larger at lower energies making a solar low-energy experiment an optimum place to search for this effect. At present, the strongest limit on neutrino magnetic moments is for $\mu(\nu_e) < 1.5 \times 10^{-10}$ Bohr magnetons. *Preliminary estimates indicate that the current limit could be improved by an order of magnitude in future solar ν experiments that measure the ES of p-p neutrinos.*

Comparison / Complementarity with Other Types of Oscillation Experiments

See separate document by the Working group leaders: Shaevitz/Barger (neutrino oscillations) and Bowles/Gonzalez-Garcia (solar neutrinos).

Supernovae

The physics of supernovae is rich and complex. Neutrinos are believed to be the primary driver for the explosion and provide the most sensitive probe of core collapse physics, including the explosion mechanism, proto neutron star cooling, quark matter, and black hole formation. Since the couplings of ν_e, $\bar{\nu}_e$, and ν_μ / ν_τ are different, the various flavors decouple at different temperatures and thus have characteristic energy distributions. This, coupled with the high densities in supernovae, leads to the possibility of flavor oscillations playing an important role in the supernova evolution. Studies of the ν arrival time, energy spectra, and flavor composition allow us to carry out ν mass measurements with a potential sensitivity of a few eV and to understand the ν mass hierarchy and flavor transformations. In addition, the ν_e and $\bar{\nu}_e$ play important roles in the nucleosynthesis reactions that occur in the supernova environment. The possibility of sterile neutrinos and flavor oscillations may play a critical role in the production of heavy elements in supernova. Finally, detection of the ν burst from a supernova provides a means to provide an early warning to the astronomy community, providing the opportunity to see first light from the supernova, an important ability in understanding supernova dynamics.

Solar ν detectors are also superb supernova detectors. With their low energy threshold, large mass, and low backgrounds, they are able to observe supernova at long times following the explosion. They *are able to identify the ν flavor and provide the only means of measuring the ν_e energy spectrum from a supernova.* In order to observe ≈100 inverse beta decay events (from ν_e and ν_e each) from a galactic supernova at 10 kpc requires detector masses of several hundred tons. Another potential reaction is ν-nucleus coherent scattering, which is primarily sensitive to higher energy ν_μ and ν_τ. This reaction provides spectral information and rates ranging from 1 event/ton for ^{4}He to 31 events/ton for Xe. Dedicated supernova detectors (such as LVD and the proposed Omnis detector) provide the long-term coverage required for supernova observation (≈ 1/30 yrs) and the ability to address important physics issues. The very large proton decay and long-baseline experiments (such as UNO and LANND) provide the opportunity to observe ES reactions with rates of 10^4-10^5 events, allowing detailed studies of supernova evolution and neutrino mixing effects and, for the first time, sensitivity to extragalactic supernovae.

Opportunity for an Underground Accelerator

The prediction of the SSM ν fluxes has been hampered by the uncertainties in the associated nuclear reaction rates. The uncertainties are even larger in charged-particle reactions that drive late stellar evolution and are responsible for neutron production in the s-process, which feeds the formation of heavy elements up to Pb. The experimental study of these reactions has been a major goal in nuclear astrophysics for the last three decades. *The installation of an accelerator laboratory at an underground (u/g) location, coupled with the utilization of recent accelerator, detector, and data handling technology could lead to a major breakthrough in our understanding of the formation of the elements.*

The LUNA accelerator at the Gran Sasso Laboratory has succeeded in making the first nuclear reaction measurements at stellar temperature conditions. However, LUNA is too limited in scope and size to maintain a successful nuclear astrophysics program beyond the measurement of pp-chain reactions. Thus, the US community proposes the development of a dedicated u/g accelerator facility with capabilities far beyond those available at LUNA. While recognizing the advantages of a cosmic ray-free environment for low cross section reaction studies, the US groups propose to complement the passive shielding conditions with the latest detector technology to allow active event identification and background reduction. This will improve the signal/background considerably by identifying and reducing beam-induced backgrounds. The implementation of new, commercially available accelerator technology will provide one to two orders of magnitude higher beam intensities.

The study of stellar He burning processes also requires substantially higher beam energies than those available at LUNA. The development of a high-intensity ECR source will allow the future application of inverse kinematics techniques for stellar reaction studies. A depth of 4000 mwe is required to suppress cosmic ray-induced neutrons. The laboratory needs at least 20w x 35d x 10h m, with an overhead crane, and expansion space should be planned for to allow for the installation of a recoil separator.

The proposal of such a facility requires careful study and preparation of the necessary experimental techniques. The simulation of u/g detection techniques will be performed in collaboration with the LUNA group and the development of active shielding and event-tracking techniques will be developed at US low-energy accelerator facilities. This program will require a few years of effort, and thus we anticipate that an u/g accelerator could be one of the first facilities installed at NUSL.

Facility Requirements

There are a number of experiments under active development in the US: for the CC reaction - Hybrid, LENS, and Moon; for ES - CLEAN and Heron; and for ES with separation into CC and NC - TPC. It is expected that at least two of these experiments will submit full proposals within the next two years. With the exception of TPC (which requests a depth of 2000 mwe), all of the experiments need depths of 3000-7000 mwe and all would benefit by being very deep.

The volumes required range from 4000 to 50,000 m^3. Electrical power requirements range from 200 to 1000 kW (for the accelerator). All need clean conditions and have extremely high radiopurity requirements. All of the experiments require underground storage space during construction (to reduce cosmogenic backgrounds) and several require underground fabrication (e.g., electroformed Cu) of components. The experiments present a number of significant safety concerns (e.g., large volumes of cryogens and scintillator, high pressures). It is clear that all of the experiments would substantially benefit from centralized services (e.g., Rn-free N_2) and a low-background counting facility.

Multiple-Use Capabilities of Solar Neutrino Detectors

The proposed experiments all have one feature in common: a low energy threshold. This allows the solar ν detectors to study a wide range of physics including $\beta\beta$ decay, dark matter, ν magnetic moment, supernovae, and geophysical neutrinos. For example, Moon is designed primarily as a $0\nu\ \beta\beta$ experiment with the capability to reach $m_\nu \approx 50$ meV and is also sensitive to the CC interaction of p-p and ^{7}Be neutrinos. The ES experiments are sensitive to recoil nuclei from WIMP interactions and have large (multi-ton) masses. How competitive they are depends on the WIMP mass and the backgrounds that can be achieved, which remain to be seen. The ES experiments can likely achieve a sensitivity to a ν magnetic moment of $\approx 10^{-11}$ Bohr magnetons. Both the CC and ES experiments would provide good sensitivity to a supernova with low energy thresholds and the ability to discriminate between ν_e, $\bar{\nu}_e$, □□□ ν_μ / ν_τ. The proposal that the Earth's core is fueled by a nuclear reactor can be tested using geographically separated low-energy $\bar{\nu}_e$ detectors, which is within the capabilities of some of the proposed CC detectors.

E&O Opportunities

Students, teachers, and the public find this area of physics to be very exciting. E&O efforts are included from "the ground up" in the proposed research. Many of the experiments are small to medium in scale and the physics is interesting and accessible to a broad range of students. The research allows students and teachers to participate in multi-disciplinary research that includes atomic, molecular, nuclear, and particle physics, and astrophysics and cosmology. The experiments employ a wide range of state-of-the art technology that in turn makes the project very attractive for undergraduate and graduate student involvement, providing a very real exposure to forefront physics

Conclusions

- Future solar neutrino experiments will provide a stringent test of the Standard Solar Model.
- Future progress in understanding the complete neutrino mixing matrix requires an active program in low-energy solar neutrino experiments.
- Future solar neutrino research requires a deep (>4000 mwe) and dedicated underground laboratory.
- An underground accelerator facility would allow significant progress in our understanding of stellar processes and should be included in the plans for NUSL.
- This research program would benefit significantly from the centralized infrastructure at NUSL.

** This report incorporates input from the 70 participants who registered for this working group. In addition, the report findings were coordinated with the leaders of the double beta decay, dark matter, long-baseline, and low-level counting working groups.*